EIC Detector R&D Progress Report

The EIC Tracking and PID Consortium
(eRD6 Consortium)

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The eRD6 Consortium

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Project Name: Tracking & PID detector R&D towards an EIC detector

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0.1 Summary Page: Barrel Tracker with TPC

A Time Projection Chamber (TPC) is one of the preferred detector options for central tracking and PID in an EIC detector due to its low mass, precision tracking, pattern recognition, and particle identification capabilities. We support building a TPC with roughly a 1 m drift length in both the hadron and electron-going directions that utilizes a thin field cage and a low mass endcap readout plane, equipped with a high resolution MPGD detector for collecting, amplifying, and reading out the collected drift charge.

0.1.1 Accomplishments to date

The following is a list of TPC-related R&D items we have investigated over the last decade in connection with the eRD6 consortium:

1. Gas characterization measurements: drift velocity, transverse diffusion, absolute gain, attachment, IBF, energy resolution
2. Readout plane optimization: the development of zigzag interleaved readouts for enhanced charge sharing to reduce channel count while maintaining excellent position resolution and uniformity of response (a first iteration of this process was already done for the sPHENIX TPC)
3. Recent developments of a 2D interleaved readout may allow for the possibility to enhance charge sharing (and in turn improve the position resolution) in a direction orthogonal to the pad rows
4. Bipolar gating grid studies: a passive gating grid option that avoids disrupting data taking in a high rate environment
5. Investigations into various MPGD-based gain elements: 4GEM, Micromegas, μRWELL, and Micromegas + 2GEM
6. Construction of a "mini-TPC" prototype and a TPC prototype with a larger cylindrical field cage enabled developments in track reconstruction using test beam measurements of the position resolution, angular resolution, N_{eff}, and transverse diffusion in a candidate gas
7. Development of laser-based calibration schemes for a TPC: line laser tracks and rapid (15kHz) generation of reference clusters from an array of strip photocathodes deposited onto field cage cathode
8. Tested streaming DAQ candidate: SAMPA front end electronics were used to read out two different prototype TPC detectors in both a lab setting and at a test beam. We also tested the DREAM front end electronics where steaming is possible, but at a relatively low rate.

0.1.2 Technological readiness

In addition to the various R&D items listed above, several members of our consortium are directly involved in the effort to build the sPHENIX TPC for measuring collisions at RHIC. Many important aspects of assembling this TPC that have been learned can be used to construct a TPC at EIC. They include the following and provide an indication of the technological readiness for this detector:

1. The development of techniques to minimize space charge, including an understanding for making an appropriate gas choice, the employment of a bipolar gating grid, and operating a 4GEM readout with an optimized field configuration to minimize IBF have been demonstrated.
2. We are in the process of developing methods for a superior dE/dx measurement, including employing a cluster counting technique (in addition to using a truncated Landau mean) and choosing a working gas with a large total ionization yield to secondary ionization yield ratio (n_T/n_p) for reducing the high energy Landau tails.

3. We have in place well thought out and proven manufacturing/assembly techniques for building the TPC support structure, GEM assembly (and QA), thin field cage and cathode assembly, and have gained engineering expertise for identifying critical infrastructure and installation requirements.
4. We have in place a good model for the full electronics chain for the DAQ system.
5. We have in place methods and simulation tools to correct for space charge distortions, including a space charge model in the TPC. The role of an outer tracking layer to aid the TPC in these corrections is also well defined, and we have implemented a laser-based calibration system that can serve as a model for a future, similar system.

0.1.3 Work remaining for a TDR

The work remaining to generate a TDR for a new TPC at EIC is extensive and goes beyond the purview of our group. However, based on our experience, the work to be done includes, but is not limited to the following:

1. Further optimization studies: IBF vs energy resolution; choice of optimal working gas for dE/dx; final design of anode pad plane; determination of optimal running parameters like the drift velocity and gain; determination of the front end electronics requirements like the shaping time and dynamic range
2. Development of an endcap design with less material compared to the sPHENIX TPC
3. Determination of what acceptance and resolution is sufficient at the EIC, including the number of pad rows the spatial resolution, and how these interplay with other tracking detectors (e.g., silicon vertex) and their impact on the overall dimensions of the detector
4. Scaling current sPHENIX data taking rate capability to better match EIC collision rate

0.1.4 Cost estimate and timeline

Because the design of a full TPC at EIC is beyond the purview of our group, it would be impractical at this time to provide an estimate of the cost and a timeline for the completion of this project. However, based on our experience in developing the design for the sPHENIX TPC, we estimate that in order to complete a TPC design for EIC that would be ready for a TDR, this would take on the order of two years (including prototyping) and cost between \$200K - \$300K.

0.2 Summary Page: Barrel Tracker with Cylindrical Micromegas

In the central pseudorapidity region of an EIC detector, the silicon vertex detector can be complemented by a low material budget MPGD tracker instead of a TPC. The goal is to study the feasibility and the impact on tracking performance of several concentric layers of Micromegas tiles.

Accomplishments to date

The performance of a Micromegas tracker solution has been tested with full Geant4 simulations of the EIC central barrel detector where the TPC has been substituted with a set of Micromegas layers. Each layer consists of 50 cm wide curved detector elements (tiles), long enough to cover the range $|\eta| < 1$. Each tile has a 2D readout and the spatial resolutions both in the z and the $r \cdot \varphi$ directions are assumed to be 150 μm. The detailed implementation in simulation of each tile is based on the technology developed for the CLAS12 barrel Micromegas tracker: the material budget in the active area of each detector is about $\sim 0.3\%$ X/X_0.

Several configurations of five and six layers have been simulated. Results included in the Yellow Report show, both in terms of material budget and tracking performance, that a Micromegas tracker is within the requirements and it is competitive with the nominal TPC implementation.

Studies on how to reduce even further the material budget have started. We plan to focus on how to simplify production and installation. A PCB-less planar design is being investigated as the potential solution for the basic tile of a modular tracker.

Technological readiness

The 1D readout curved Micromegas technology has been successfully installed in the CLAS12 experiment. Also with a 2D readout, this solution will meet the requirements in terms of material budget.

Work remaining for a TDR

- **Curved Micromegas:** test the 2D readout, possibly with zigzag readout patterns, to confirm the production feasibility and the spatial resolution for the resistive technology; design a light support structure for the whole tracker.
- **Very low material budget planar Micromegas:** implement the list of materials in simulation; study the optimal configuration for a full tracker based on a modular design; build and test a demonstrator prototype.

Cost estimate and timeline

For the low material budget Micromegas a small scale demonstrator will be build this year. For the 2D readout, studies on the readout pattern and the resistive material will be carried out in order to optimise the spatial resolution: a small batch of readout prototypes should be foreseen. Tests with cosmic rays will be performed at Saclay. Travel money for beam tests should be foreseen.

0.3 Summary Page: Fast Tracking Layer with Cylindrical μRWELL

In the central detector region, we envision implementing at least one thin (few cm in radius) cylindrical μRWELL layer just outside the main tracker volume. This layer will provide fast timing information for vertex identification and it will also seed particle identification by providing precise track impact points and directional information for particles that impinge on a PID detector, e.g. a DIRC, located directly behind this μRWELL layer.

Accomplishments to date: The impact of a cylindrical μRWELL layer on the reconstructed angular resolution of tracks was studied within the EicRoot simulation framework. The cylindrical layers were placed in the central region ($|\eta| < 1$) at various radial positions. We found significant improvement in the angular track resolution when layers were placed radially in front and behind a DIRC (see previous eRD6 reports).

With these encouraging results from the initial simulation, we began designing a prototype concept. We are working with CERN to produce a low-mass version of the composite μRWELL foil with reduced thickness of the PCB substrate and the readout layer. In parallel we are working on the mechanical support structure for a cylindrical μRWELL detector. We have successfully designed and constructed a small mechanical mock-up of the detector using Kapton foils and a 3D-printed support structure.

Technological readiness: Planar μRWELL detectors have been demonstrated by others and by our consortium to be a viable MPGD with good performance characteristics for tracking applications. A fully functional cylindrical μRWELL detector is yet to be demonstrated.

Work remaining for a TDR: A small functional cylindrical μRWELL prototype ($\sim$ 20 cm diameter and $\sim$ 55 cm length) needs to be built and tested in beam. The detector will be operated in μTPC mode to provide tracklet information. It will need to be assessed for mechanical stability and tracking performance. The mechanical design of this prototype and its support structure is underway within eRD6 via the R&D on the mechanical mock-up.

Cost estimate and timeline for small functional cylindrical prototype with μRWELL layer: Up to the TDR, we estimate the core cost for procuring active detector components (foils), mechanics, electronics, and for production of the prototype to be \$25k. Performance tests in a beam will require an extra \$15k for travel between institutions and to Fermilab. Personnel costs (graduate students) are estimated at \$50k per year. The total estimated cost is \$140k over two years. With proper funding this development phase is expected to be completed in two years, including test beam effort and analysis of results (assuming no delays related to COVID-19).

0.4 Summary Page: Endcap Trackers with MPGDs

Large-area planar MPGD trackers can be used in the forward and backward endcap regions to provide global tracking as well as local positional information for a PID detector located behind the forward tracker, such as a RICH detector. The candidate technologies under consideration by our consortium for this application are Triple-GEMs and μRWELL detectors.

Accomplishments to date: Large-area ($\sim$1 m long) GEM foils and mounting frames have been designed specifically for use in an EIC detector and with minimization of material in the active area in mind. These foils and frames were used to construct two large-area and low-mass Triple-GEM prototype detectors. Each prototype uses a distinct assembly and readout technique. One prototype detector was tested successfully in a proton beam at Fermilab. The other one is being refurbished to improve mechanical stability of the frames. Small-area ($\sim$ 100 cm^2) generic μRWELL detectors were also successfully built and tested in the same beam.

Technological readiness

- **GEM**: GEMs represent mature technology whose performance and limitations are well known. Large-area Triple-GEM detectors are being used in a number of large nuclear and particle physics experiments.
- **μRWELL**: μRWELLs are a more recent MPGD technology and have been demonstrated to be a viable tracking option.

Work remaining for a TDR:

- **GEM**: A final technical design has to be produced following guidance from the prototyping and simulation results and validated in a beam test.
- **μRWELL**: Jefferson Lab has recently dedicated R&D efforts towards developing large-area μRWELLs for use in their future experiments. One of our consortium members (UVa) is directly participating in that effort.
- **Low-mass μRWELL Foil**: The material budget of the current standard μRWELLs available from CERN needs to be reduced in order to better fit within the EIC material budget, in particular in the backward direction where the material budget is critical for electron tracking. This involves reducing the thickness of the flexible PCB that the μRWELL is mounted on and making a transition from readout board to readout foils. We are working with CERN to produce such a low-mass μRWELL foil.

Cost estimate and timeline: For the Triple-GEM prototypes, no additional funds are needed beyond what has already been funded. It is expected that the large-area μRWELL R&D at Jefferson Lab will be completed within a year. We will be following that R&D development closely and decide at the time of its completion if further R&D is needed for an application of planar μRWELL detectors in an EIC detector.

0.5 Summary Page: Development of MPGDs for High Momentum Hadron PID

MPGDs-based single photon detectors are developed for Cherenkov imaging applications, using as starting point the hybrid MPGDs in use since 2016 in COMPASS RICH. In the EIC context, the typical collider-type setup imposes a compact design of the RICH for High Momentum Hadron PID. When gaseous photon detectors are used, a compact RICH can be obtained using the windowless approach with the radiator gas also used as the gaseous detector gas. It is so possible to detect very far UV photons (∼120nm), where the photon yield is more abundant and, therefore, the radiator can be short $\mathcal{O}(1 \text{ m})$. The R&D is performed along two development lines, whose status is separately discussed in the following.

0.5.1 Development of MPGD sensors of single photons

Development Goal - The hybrid MPGDs of single photons have to be upgraded in order to meet the needs of a compact RICH. The main development lines are the miniaturization of the read-out pads required because of the short lever arm and the validation of the read-out with the VMM3 front-end chip for the specific application of single photon detection. VMM3 is expected to provide very low noise figures also for detectors with non-negligible capacitance and its architecture is adequate for data acquisition based on streaming read-out models.

Accomplishments to Date - A first version prototype with miniaturized pad-size was realized and characterized, also in test beam. The second version is under construction. Preparatory activity in order to read-out the second prototype with VMM3 front-end has been performed. This includes the procurement of the electronics boards and preliminary exercises to read-out the front-end chip. The progress of this activity has been heavily penalized by the restrictions imposed by the pandemic emergency.

Technological Readiness - The prototype has been demonstrated in a test beam environment.

Work remaining for a TDR - The completion of the R&D development, expected in 24 months and, in parallel, a complete simulation of a gaseous RICH making use of these detectors.

Cost estimate and timelines - The planned activity can be completed within 12 months if no further delay is imposed by the persisting limitations related to the pandemic emergency. No further financial resources are needed for next year as part of the already allocated resources could not be used due to the pandemic emergency. On the contrary, standard level of financial support is needed for the last year of the activity corresponding to about 40k$.

0.5.2 New Photocathode Materials for gaseous detector

Development Goal - So far, CsI is the only photoconverter successfully used in gaseous detectors. It is fragile due to its chemical reactivity to water vapor and because the bombardment of the ions created in in the multiplication process degrades the Quantum Efficiency (QE). The proposed novel photoconverter by Hydrogenated NanoDiamond (H-ND) powder is expected to be more robust, as confirmed by the initial studies. The development aims at establishing the use of photoconverters by H-ND in gaseous detectors and determine the key parameter of ND powders to obtain maximum and reproducible QE.

Accomplishments to Date - The assessment of the compatibility of the novel photoconverter with gaseous detectors is well advanced. The identification of the key parameters for high and reproducible quantum efficiency of the ND powder is at an initial stage.

Technological Readiness - Prototypes have been demonstrated in laboratory environment.

Work remaining for a TDR - This being a highly innovative development, it requires another three or fours year for completion. If successful, it will represent an upgrade of the MPGD sensors of single photons. Therefore, this option can appear in a TDR only as potential improvement of a baseline design with CsI.

Cost estimate and timelines - Support at the level of 30k$/y is needed during the completion period: about 100 k$ in total.

0.6 Summary Page: New Radiator Materials for PID

The investigation towards new radiator materials for PID belongs into the category of blue skies research and can therefore not be addressed in the context of this summary.

0.7 Summary Page: Large Mirror Development

The installation of the PVD equipment has been finalized, the commissioning of the device has been established and the remaining task is to gain experience with the PVD process for certain applications. It can be concluded that the PVD device is ready for use.